Paper

DESIGN CRITERIA FOR PROMPT RADIATION LIMITS ON THE RELATIVISTIC HEAVY ION COLLIDER SITE

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Abstract—**The Relativistic Heavy Ion Collider (RHIC) is a superconducting colliding beam accelerator facility that is currently under construction. Relatively small amounts of energy depositing in the coils of superconducting magnets can result in a "quench," the irreversible transition to the normal resistive state. The quench limit of superconducting magnets, therefore, constrains local beam loss throughout the injection, acceleration, and storage cycles to extremely low levels. From a practical standpoint, it follows that there is essentially no prompt radiation in most regions due to normal operations. The design of shielding is, therefore, principally driven by the consequences of a single pulse fault at full energy in one of the two storage rings. Since there are no regulatory requirements or guidance documents that prescribe radiological performance goals for this situation, the RHIC Project has proposed a scheme to classify the various areas of the RHIC complex based on Design Basis Accident faults. The criteria is then compared to existing regulatory requirements and guidance recommendations.**
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Key words: accelerators; safety standards; exposure, radiation; regulations

INTRODUCTION

THE SCOPE of the RHIC Project is to design, construct, and bring into operation a colliding beam facility which will enable studies of nuclear phenomena in relativistic energy heavy ion collisions. The collider, which consists of two concentric rings of superconducting magnets, will be constructed in an existing ring tunnel of ~3.8 km circumference located in the northwest section of the Brookhaven National Laboratory (BNL) site. Fig. 1 depicts the layout of the facility. The collider is to be able to accelerate and store counter-rotating beams of ions, ranging from hydrogen (protons) to gold, up to kinetic energies of 100 GeV/u (GeV per nucleon) for gold ions and 250 GeV for protons. The store duration for gold in the energy range of 30 to 100 GeV/u is expected to be approximately 10 h. The layout of the tunnel and the magnet lattice enables the two rings to intersect at six locations along their circumference where the counter-rotating beams can collide. An existing complex of accelerators, i.e., Tandem Van de Graaff, Booster Synchrotron, and Alternating Gradient Synchrotron (AGS), will be used to accelerate ions for injection into the collider. The scope of the project, therefore, includes construction of the beam transfer lines from the AGS to the collider, together with an

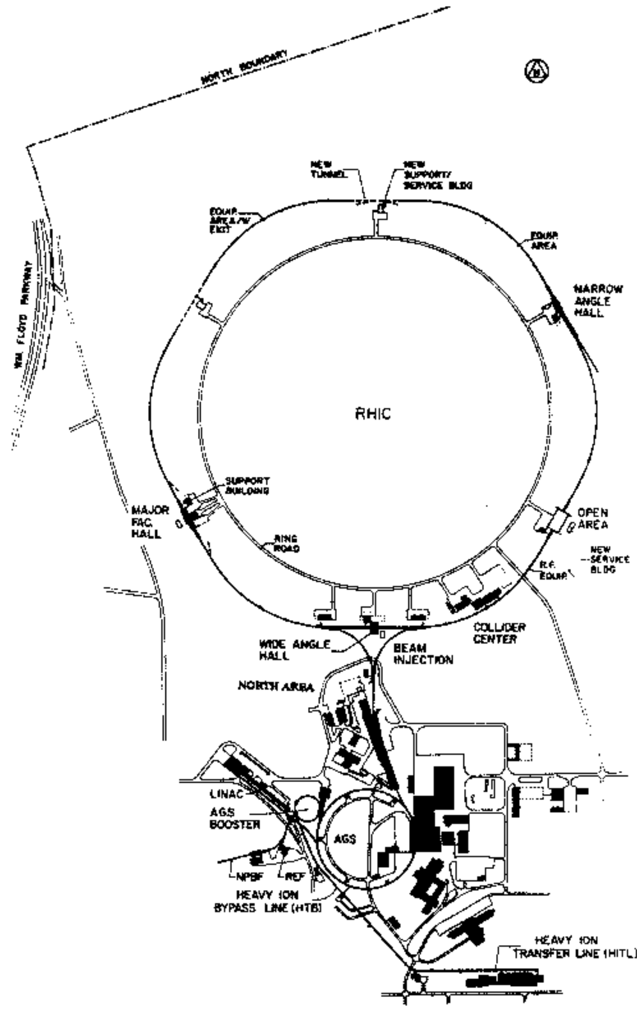

Fig. 1. RHIC Site Map

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initial complement of detectors to exploit RHIC's physics potential.

The purpose of this paper is to discuss design goals for limits on prompt radiation (including skyshine) which have been proposed for locations associated with the RHIC site. In general, the limit for any given location (radiological control area) is achieved by a combination of passive shielding and active beam loss controls. Transition from one location to another with a higher limit involves passage through a "barrier" which can range from a warning sign to physical barriers such as locked gates or interlocked shield doors. Regulation of this passage is the subject matter of access control, which is only briefly mentioned below, but is not discussed in any detail.

Normal beam loss in a superconducting collider such as RHIC must be small for the collider to efficiently operate. However, some potential for worst-case faults exists which may dominate the passive shielding requirement in a given location. In practice, the radiological controls and posting employed to mitigate the hazards caused by beam loss will be consistent with regulatory requirements (U.S. DOE N 1992). However, at most locations surrounding a superconducting accelerator, the maximum possible radiation field corresponds to the improbable occurrence of losing an entire beam at full energy due to a fault. Unfortunately, standards such as those used for protection of the general public were not intended to apply to this type of (short duration) radiation field or scenario. They are more appropriately applied when the dose equivalent is delivered over long time frames with high probabilities of occurrence (i.e., the regulations do not set limits on the definition of an uncontrolled area for accelerator "accidents"). Because the existing regulatory and guidance documents do not explicitly address fault scenarios for RHIC beam loss, a scheme to provide guidance for shielding design and a means to classify a hierarchy for the internal use by designers are developed in this paper.

A brief summary of the beam loss scenario in RHIC[†] precedes specification of the proposed criteria.

BEAM LOSS IN THE RHIC FACILITY

Systematic beam losses in a superconducting accelerator are limited by the ability of the magnets to sustain their superconducting state in the presence of particle losses. Particles leaving the beam pipe of the accelerator deposit energy in the form of a cascade of hadronic and electromagnetic particles. These interactions typically give rise to a significant temperature rise which is, at a maximum, several meters from the initial interaction point. A temperature rise of more than 0.5° K is sufficient to destroy the superconducting state of the Nb-Ti wire (a quench) causing the magnetic stored energy in the system to be dumped very rapidly into the superconducting cable which causes a further temperature increase of typically 50° K. Several hours are then required to cool the magnets back down to the 4° K operating temperature. During this time, the accelerator is non-operational. The amount of energy needed to initiate a magnet quench is ~4 mJ/g of superconductor and can be achieved by a loss of as little as 1 part in 10^4 of the circulating beam. Since such a small amount of beam loss can cause significant disruption to the operating program, superconducting accelerators are effectively loss-free during normal operations. Small amounts of particle losses are intercepted by collimators, beam scrapers, and a rapid acting (<1 ms) beam removal system that is used to protect the magnets from the onset of beam loss by directing the beam onto a well shielded external beam dump.

It should be noted that when beam loss occurs, there is typically 3.97 m of sand shielding over the collider and transfer line. An additional 1.8 m of sand is over the collider in the vicinity of the collider center, which is occupied by non-radiation workers, and, for the purpose of ALARA, over the collider beam dump.

Collider

Normal beam loss. Normal beam loss mechanisms are dominated by intrabeam scattering and Coulomb processes for heavy ions and by nuclear interactions for protons. An estimate of the location of annual loss is shown in Table 1.

In this table, Limiting Aperture Collimators (LACs) and "Other Points" refer to magnets on which the primary beam interacts due to LAC inefficiency. The vast majority of annual loss occurs on the internal beam dump or on an LAC which are well-shielded locations.

The maximum loss rate in an hour is determined by the set-up procedure to be 5.7×10^{11} Au ions in both rings at 100 GeV/u equivalent or 2.85×10^{13} protons at 250 GeV plus 2.85×10^{11} Au ions at 100 GeV/u equivalent.

Table 1. Beam losses.

Location	Annual loss Au at 100 GeV/u ($\times 10^{14}$)	Annual loss Protons at 250 GeV ($\times 10^{16}$)
Dump	7.616	1.343
LACs	1.270	0.024
Crossing point	0.185	0.006
Other points	0.212	0.004
Beam-gas	0.031	0.002

[†] Harrison, M.; Stevens, A. J. Beam loss scenario in RHIC. Upton, NY: Brookhaven National Laboratory; AD/RHIC/RD-52; January 1993. The entries in Table 1 follow from a model of operations which divides a year into A, A (heavy ions in both rings) and p, A (protons in one ring) cycles. Each cycle, in turn, consists of a set-up fill followed by a physics run fill. The (somewhat complex) mechanisms for anticipated beam loss depend on both ion species and fill type and are not reproduced here.

Design-basis accident fault. A worst-case fault in the collider would be the loss of the full beam at full energy at an arbitrary point (any magnet or device which intrudes into the physical aperture). Harrison and Stevens[†] concluded that the maximum credible fault would be full beam loss at points which are near the limiting aperture of the collider and loss of one half of the full beam at other locations, and that such occurrences should be allowed for at a rate of once in several years. For the purpose of evaluating necessary shielding and access restrictions as applied to a specific location, the design-basis accident (DBA) will be assumed to be the maximum credible fault once per year.

Other faults. Proper control of beams in the collider will, of course, involve a "learning curve;" beam intensity will grow to the design intensity only as progress is made on the ability to handle beams cleanly. Nevertheless, beam loss will occur with a resulting magnet quench which terminates a run. A recent simulation of scraping on a magnet[‡] indicates that $\sim 10^9$ 250 GeV protons interacting on a magnet will cause a quench. The "beam loss scenario" suggests that a reasonable allowance for these "normal faults" would be 20 per year.[†]

Transfer line

Normal beam loss. Beam losses in the AGS North Experimental Area have been measured to be less than 0.1% of the beam over the entire length of the U-line during normal operation and less than 0.03% on a single magnet.[§] Normal beam loss in the transfer line is, therefore, based on the assumption that 0.1% of the beam can be lost in the entire line, and that half of this (0.05%) will be lost at an arbitrary point. The maximum annual radiation burden from prompt radiation and induced activity in soil and air is bounded by loss of 17.55×10^{11} Au ions at 10.4 GeV/u plus 18.24×10^{12} protons at 28 GeV. The maximum loss in an hour, again determined by the set-up procedure, is 1.65×10^9 Au ions at 10.4 GeV/u (Au, Au running) or 6.78×10^{10} protons at 28 GeV (p, Au running) plus 8.28×10^8 Au ions at 10.4 GeV/u where, again, half of these losses occur at a single point.

In addition to these uncontrolled, but small, beam loss levels, beam "loss" in the more general sense will also occur on a beam dump in the transfer line during periods of diagnostic studies and injection line set-up.

Design basis accident fault. In the case of component failure (e.g., a shorted coil) or a drastically missteered beam, the full injected beam (equivalent to 1.2×10^{12} protons s^{-1} at 28 GeV) can fault on a magnet in the transfer line. It is assumed that the personnel protection system using fail-safe interlocked radiation detectors [e.g., Chipmunks (Awschalom 1972)] will terminate such a condition within 2 AGS pulses. The location of these detectors will be determined by modeling of beam loss, fault studies, and review by the RHIC Radiation Safety Committee. The DBA here is five such mitigated faults per year.

Other faults. To be conservative within a realistic operating envelope, the assumption is made that 5% of the total annual fills of the transfer line have an order of magnitude higher loss (i.e., 1% of the beam) than normal.[§]

CONTROLLED AND UNCONTROLLED AREA CLASSIFICATIONS

Four area classifications are defined where personnel are allowed without restriction by physical barriers. These areas are categorized according to whether or not personnel allowed access have been trained as radiation workers (areas posted as controlled) and according to whether the occupancy is expected to be "high" (i.e., continuous as defined by 2000 h per year) or "low," defined as a region with an occupancy factor (OF) of 1/16 (1/2 h per 8 h day) or below (NCRP 1976). Regions with intermediate occupancy will be treated as if they are high occupancy areas.

Archetypes for these four area classifications are as follows:

1. Area "A": Radiation workers; high occupancy. This is typical for experimental counting houses. If assembly areas adjacent to experimental halls are required to have significant occupancy while the beam is on, these would also fall into this classification.
2. Area "B": Radiation workers; low occupancy (1/16 of or below). This area is typified by the possible need to have movable shielding inside an experimental hall where occasional access would be required for work on fast electronics modules close to detectors.
3. Area "C": Non-radiation workers; high occupancy. The occupants in this area are considered as members of the general public, with occupancy greater than 1/16. The collider center is an archetype.
4. Area "D": Non-radiation workers; low occupancy (1/16 OF or below). This classification is intended to represent (most of) the regions which physically connect the collider center to the remainder of the site and are used for transient access—roadways, parking lots, etc., and most of the berm over the collider.

PROPOSED DESIGN CRITERIA

Design criteria for dose limits for the areas described in the preceding section are proposed below. Both normal loss limitations and DBA fault limitations

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[‡] Stevens, A. J. Radiation levels at floor level from local beam loss in RHIC. AD/RHIC/RD-27; October 1991.

[§] Glenn, J. W. Brookhaven National Laboratory Memorandum to Stevens, A. J. Typical losses in FEB U Line. February 1992.

are considered. The annual dose fault limitation applies to both the transfer line and the collider.

I. Classification "A": Radiation workers; high occupancy.
   1. *Normal loss*
      0.002 mSv h^{-1}
   2. *DBA fault*
      5 mSv y^{-1} limit

II. Classification "B": Radiation workers; low occupancy.
   1. *Normal loss*
      0.032 mSv h^{-1}
   2. *DBA fault*
      10 mSv y^{-1} limit

III. Classification "C": Non-radiation workers; high occupancy.
   1. *Normal loss*
      0.15 mSv y^{-1}
   2. *DBA fault*
      0.1 mSv y^{-1} limit

IV. Classification "D": Non-radiation workers; low occupancy.
   1. *Normal loss*
      2.4 mSv y^{-1}
   2. *DBA fault*
      1.6 mSv y^{-1} limit

COMPARISON OF PROPOSED DESIGN CRITERIA WITH REGULATORY REQUIREMENTS

Existing DOE regulatory requirements do not explicitly consider low probability fault situations for accelerators (U.S. DOE 1989; U.S. DOE 1992; U.S. DOE N 1992). This proposal uses the International Commission on Radiological Protection (ICRP) concept of dose averaging (ICRP 1990) and adopts the philosophy that both low occupancy and low probability of faults mitigate allowable dose in a single year if a multi-year average dose for a given individual is acceptably low. With this in mind, this approach asserts that the allowable dose from normal loss should be well within any existing or proposed regulatory requirement, but the DBA scenario, given the fault assumptions made herein, be allowed to exceed yearly dose limitations by a small amount comparable to either (a) the annual dose from normal losses for radiation workers; or (b) an amount comparable to the natural background for non-radiation workers. In either case, it is important to realize that an actual DBA fault occurrence would most likely represent a once-in-a-lifetime event for a given individual.

Comparisons with known requirements are as follows:

1. Radiation workers
   A. The 0.002 mSv h^{-1} criteria is below the 0.005 mSv h^{-1} design goal specified in DOE Order 5480.11 (U.S. DOE 1989).
   B. The annual dose from losses of $0.002 \text{ mSv h}^{-1} \times 2000 \text{ h y}^{-1} = 4.0 \text{ mSv y}^{-1}$ is well below the Federal Dose Limit of 50 mSv y^{-1} (U.S EPA 1987), the DOE Administrative Control Level (ACL) of 20 mSv y^{-1} (U.S. DOE N 1992), and the Laboratory ACL of 12.5 mSv y^{-1}.[1]
   C. A worst-case scenario, given the assumptions specified above, would pertain to an individual who spent 15/16 of a year in a class "A" area and 1/16 of a year in a class "B" area during which he/she was exposed to 10 mSv during fault conditions. The upper limit for annual dose to this individual would be $(15/16) \times 2000 \text{ h} \times 0.002 \text{ mSv h}^{-1} + (1/16) \times 2000 \text{ h} \times 0.032 \text{ mSv h}^{-1} + 10 \text{ mSv} = 18.69 \text{ mSv}$. For the vast majority of the worker population on the RHIC site, this upper limit is not credible because shielding designed for the possibility of a fault in the region of the collider limits the normal-loss hourly dose to values far lower than specified by the criteria.[2] The most likely dose to a radiation worker exposed to an accident in a class "B" area would, therefore, be the fault value itself of 10 mSv. Of the total dose in this extremely improbable situation, 14 mSv would occur in the low-occupancy region which exceeds the design goal of 10 mSv y^{-1} in low occupancy areas in DOE Order 5480.11 Section 9.J.1.b (U.S. DOE 1989).
2. Non-radiation workers
   A. The annual normal loss dose of 0.15 mSv is below the BNL design goal of 0.25 mSv y^{-1} per facility. With allowance of a worst case fault, the goal is exactly met.
   B. A worst-case scenario would pertain to an individual who spent 15/16 of a year in a class "C" area and 1/16 of a year in a class "D" area during which he/she was exposed to 1.6 mSv during fault conditions. The maximum annual dose here would be ~ 1.89 mSv which is both comparable with natural background and is expected to represent a very rare occurrence for a given individual. In addition, it is reasonable to assume that the exposed population for this case is one person or at most a very few people.
3. Regulatory limits and guidance for the general public

   The following are the existing regulatory requirements and guidance for the general public which do not explicitly address low probability faults (Shleien 1992):

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[1] Environment safety and health standards manual. Upton, NY: Brookhaven National Laboratory; December 1992: chapter 3.

[2] Stevens, A. J. Local shielding requirements for the STAR detector. Upton, NY: Brookhaven National Laboratory; RHIC/DET Note 5; June 1992. In this reference, a shield thickness chosen to limit a fault dose equivalent to 5 mSv limited the normal loss dose equivalent from beam-beam and beam-gas collisions to 0.06 mSv y^{-1}.

ICRP-60
- Limit annual effective dose to 1.0 mSv averaged over any 5 consecutive years.

NCRP-91
- Limit annual effective dose to 1.0 mSv for continuous or repeated exposure.
- Limit annual effective dose to 5.0 mSv for infrequent exposure.

10 CFR 20
- Limit annual effective dose to 1.0 mSv.
- Limit dose in 1 h to 2.0 mSv.

DOE Order 5400.5
- Limit annual effective dose to 1.0 mSv.
- If avoidance of higher exposure is impractical, temporary limit not to exceed 5.0 mSv may be authorized.

OTHER AREA CLASSIFICATIONS/ACCESS CONTROL

Other radiation area classifications exist on the RHIC site where most people will be prohibited from entry by physical barriers. Examples include the berm on top of the collider in the vicinity of the internal dumps (likely radiation areas where the dose could be in the range of 0.05–1 mSv in one hour) and inside the RHIC tunnel enclosure [a high hazard area where the dose could exceed 0.5 Sv in one hour.[1]

As mentioned in the introduction, regulation of passage from one radiation classification to another is a part of access control. The entire subject of access control, which includes specifications for active interlocks, sweep procedures, configuration control, etc., is not in the scope of this document.

CONCLUSIONS

Four area classifications are proposed for the RHIC site for regions accessible without restriction by physical barriers. The classifications are distinguished by occupancy and by whether or not radiation worker training is required for entry. Each classification is specified by limits on dose equivalent resulting from both anticipated beam loss and from design basis accident faults. Although no explicit regulatory requirements exist for low probability faults, the highest proposed fault limits (10 mSv y^{-1} in low occupancy regions restricted to radiation workers and 1.6 mSv y^{-1} in low occupancy uncontrolled regions) are compatible with several recommendations (Shleien 1992) that consider infrequent exposures and multi-year dose averaging for given individuals.

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